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TRANSIENT TURBINE ENGINE MODELING WITH HARDWARE-IN-THE-LOOP POWER EXTRACTION (PREPRINT)

John McNichols, Michael A. Boyd, J. Mitch Wolff, Philip R. Owen, S. Danny Phillips, Mark J. Blackwelder, J. Timothy , Michael W. Corbett, and Peter T. Lamm

PC Krause and Associates, Inc.

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14. ABSTRACT
Increasingly high aircraft power demands require that the interactions between an aircraft's electrical subsystem and the engine subsystem be considered in dynamic, system-level tests. Traditionally, system-level dynamics have only been captured in completely assembled aircraft systems. Component-level or subsystem-level optimization is no longer appropriate because highly interdependent dynamics between subsystems only become apparent during system-level analysis. In an effort to mitigate program risk, enable system-level optimization, and reduce the high cost of testing integrated power and propulsion systems in an altitude-simulating wind tunnel, alternatives such as modeling and simulation can be utilized. Synchronizing and coupling simulations of vastly different time scales is possible; however, the resulting system simulation usually runs very slowly. For this reason, hardware-in-the-loop (HIL) is an ideal test platform where simulations and hardware components can be integrated for system-level testing when time scales are drastically different or actual hardware prototype components are available.

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Transient Turbine Engine Modeling with Hardware-in-the-Loop Power Extraction

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Increasingly high aircraft power demands require that the interactions between an aircraft's electrical subsystem and the engine subsystem be considered in dynamic, system-level tests. Traditionally, system-level dynamics have only been captured in completely assembled aircraft systems. Component-level or subsystem-level optimization is no longer appropriate because highly interdependent dynamics between subsystems only become apparent during system-level analysis. In an effort to mitigate program risk, enable system-level optimization, and reduce the high cost of testing integrated power and propulsion systems in an altitude-simulating wind tunnel, alternatives such as modeling and simulation can be utilized. Synchronizing and coupling simulations of vastly different time scales is possible; however, the resulting system simulation usually runs very slowly. For this reason, hardware-in-the-loop (HIL) is an ideal test platform where simulations and hardware components can be integrated for system-level testing when time scales are drastically different or actual hardware prototype components are available. The work documented in this paper demonstrates the capability of conducting propulsion/power system-level tests with a simulated engine model integrated with generator hardware. It more importantly shows that when using a validated engine model, HIL is capable of greatly reducing time, effort, and cost associated with full system hardware validation (by orders of magnitude).

I. Introduction

Aircraft are becoming more complicated and more tightly integrated systems of subsystems. This integration presents the possibility of non-linear, time-dependent interactions between the aircraft subsystems. Historically, these interactions have been neglected, with each subsystem being designed, analyzed, and tested with little consideration for system-level integration. Platform power and thermal load requirements have skyrocketed and are responsible for drastically increasing the magnitude of the dynamic interactions that exist between aircraft subsystems. While optimization has traditionally taken place at the component or subsystem level, non-linear interactions require that optimization be done at an aircraft system level. This system-level performance optimization requires advanced modeling, simulation, and integration techniques.

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Specific to the interaction between aircraft engine and power subsystems, shaft horsepower extraction from the engine has the potential to introduce torque ripple, high mechanical stress, and speed transients. These effects can in turn cause compressor stall and unacceptable thrust transients. In addition there may be thermal management issues at the component, subsystem, or system level. The same power extraction has the potential to create problems with the electrical subsystem as well. For example, large excursions in shaft speed, outside of the rated operating range can result in voltage or current transients that may cause overheating or mechanical stresses thereby reducing the life of the electrical generation system. In addition, these transients may affect the power quality of the aircraft main bus thereby impacting the electrical loads such as the radar and actuation and may result in a source transfer to back-up generation or batteries.

To properly consider dynamic interactions between aircraft subsystems, a multi-physics system simulation must be used. Computer models of different components and subsystems are often developed by different entities, which can lead to issues when trying to integrate models together. Intellectual property must be protected while allowing appropriate variables to pass between models. Enabling models to communicate with each other at all is a non-trivial issue when they are developed in different languages or programs. Distributed Heterogeneous Simulation (DHS) is a software tool that synchronizes any number of dynamic simulations in a wide variety of languages and modeling environments[1]. It allows each model to run in its own native environment on whichever platform (Windows, Linux, etc.) it prefers. Therefore, it protects the proprietary details of each model while allowing it to become part of a larger system-level simulation and can provide significant increases in simulation speed. Although DHS addresses the integration of multi-physics, multi-vendor subsystem models, such a paradigm can have limitations with respect to real-time simulation. If the provided component subsystem models do not execute faster than real-time or if the system dynamics require significant bandwidth, the integrated system simulation speed may not be sufficient. This is especially problematic when coupling models that are interested in drastically different time scales. An example would be coupling a detailed generator model (time steps on the order of microseconds), an engine model (time steps on the order of milliseconds), a thermal management model (on the order of seconds or minutes), and a flight mission controller (on the order of hours). In this scenario, getting meaningful flight mission controller data would require the generator model to execute for hours of simulation time which may equate to several days of execution time.

Practical system-level integration requires using an alternative or complementary solution. One such approach is hardware-in-the-loop (HIL). This technique integrates one or more simulations with tangible pieces of hardware. In order to perform a meaningful HIL test the system must run exactly real-time – the only useful time scale for hardware. The real-time constraint presents benefits and challenges. Where simulation of system components is used, the model complexity must ensure that the system achieves real-time execution at every time step. Furthermore, it must be compatible with a real-time operating system that is capable of running the simulation. For some models, especially those that use large time steps, this may mean running the model orders of magnitude more slowly than the computational limit of the computer on which it runs. However, HIL also enables hardware to be used in place of models whose complexity would render it impossible to meet real-time simulation constraints. HIL facilitates the ideal combination of hardware and software as long as it is possible to properly interface each piece into a whole system.

II. Motivation

In 2005, a Rolls-Royce engine was tested in an altitude-simulating wind tunnel and was put through a series of throttle and power extraction transients. This type of testing is extremely expensive both in terms of manpower and money. For this reason, the number of hardware engine tests conducted was limited. It would be beneficial to be able to run additional tests of the same configuration to investigate flight envelope regimes not investigated in these tests. However, this requires a combination of a dynamic model that accurately represents the engine and generator hardware, integrated at the system-level using HIL as mentioned in the previous section. This paper documents the ability of HIL to give the same results as the all-hardware experiment by coupling a dynamic engine model with the same generator hardware used in the 2005 engine tests.

III. Dynamic Engine Modeling

The dynamic engine model used in this study is composed of two parts: a model of the aerodynamics, thermodynamics, and relevant mechanical dynamics of the engine itself, and a model of the engine's control. The engine cycle is modeled using the Rolls-Royce proprietary program TERMAP (Turbine Engine Reverse Modeling Aid Program). This Fortran program employs a Newton-Raphson iterative technique to converge a series of non-linear algebraic and discretized differential equations representing continuity of flow, balance of forces,

conservation of energy, and satisfaction of boundary conditions throughout the engine cycle. The program is concerned primarily with a one-dimensional idealization of the flow, with uniform properties assumed at a series of stations. Components such as compressor or turbine stages, combustors, ducts, mixers, nozzles, etc. model the change in properties between stations. The primary dynamic effect modeled is that of rotating component acceleration and deceleration under the influence of imbalanced torques, although other effects such as volume dynamics, heat storage, and transient tip clearance changes can also be modeled. Since an iterative algorithm is employed to resolve the cycle at each time step, real-time performance is achieved by limiting the number of iterations allowed. This allows the possibility that full convergence may not be achieved at every time step. Part of the model development involves careful testing of real-time and non-real-time simulations to ensure that full convergence is achieved for the vast majority of time steps and that any occasional convergence failures do not materially affect overall results.

The control, a full-authority digital engine control (FADEC), is modeled in Simulink. The model includes the full power management and operability logic of the hardware control, discrete sampling of measured parameters, signal conditioning and processing, and models of any analog circuitry that is part of the complete control package. There is provision for introducing noise into feedback signals. The static and dynamic behavior of hardware elements such as the fuel pump and metering unit (FPMU), various actuators, and instrumentation is also modeled. The hardware FADEC allows custom modification of certain constants affecting the control logic (such as selected gains and rate limits). The model allows similar modifications so that the simulated control accurately models the control as configured in the altitude test.

The control receives as inputs the throttle lever angle (TLA), several items from the aircraft flight data computer, and measured shaft speeds, pressures, and temperatures from the engine. It governs compressor variable geometry (CVG) position and fuel flow to the engine. The simulation makes available information pertaining to logic decisions within the control, measurements available from running a real engine, and a host of additional parameters of interest that would not be available from full hardware testing including all cycle pressures and temperatures, air flow rates, component efficiencies, and stability margins.

The control and engine model are coupled by using a Simulink S-function to call the TERMAP model of the engine. The S-function code itself is written in C. Since the engine model is called through Simulink, the problem of interfacing the engine/control model to a real-time operating system and associated lab hardware becomes a problem of interfacing these elements to Simulink. To avoid frequency aliasing of transient results, the engine model is called with discrete time steps no larger than half the sample time of the control logic. A multi-rate simulation results, but is practical for real-time execution because the time steps involved span at most a single order of magnitude rather than the several orders of magnitude required for detailed simulation of all components (as described earlier). DHS has been used to couple a similar engine/control model to detailed models of the generator and other electrical components. The extremely short time steps required for accurate simulation of some of these components produced a system simulation that executed about two orders of magnitude slower than real-time, and hence was not practical for long mission profiles that required hours of simulated time.

IV. Hardware-in-the-Loop Test Configuration

A. Hardware/Software Interface

The key to being able to couple the simulated engine with the electrical system hardware is the ability to run the model in real-time. This requires the use of a real-time operating system and a compatible I/O (input/output) board. Figure 1 illustrates the HIL configuration used. It shows that on the simulation side, there is a single real-time computer that is capable of running the combined engine and FADEC model. On the hardware side is a 350 horsepower motor drive stand, the same DC generator that was used in the 2005 engine tests, and a resistive load bank. The resistive load bank has a real-time programmable configuration so that the resistive load applied to the generator can be controlled in real-time. The drive stand is capable of being speed controlled using a ±10 VDC signal (10 VDC for each direction of rotation). The linear relationship between voltage and speed was documented by Ramalingam, et al., who also demonstrated the ability of the drive stand to respond quickly enough to accurately emulate this class of engine[2]. In a separate effort, a generic engine simulation was interfaced with a generator to show proof of concept for conducting HIL studies with an engine simulation and generator hardware[3].

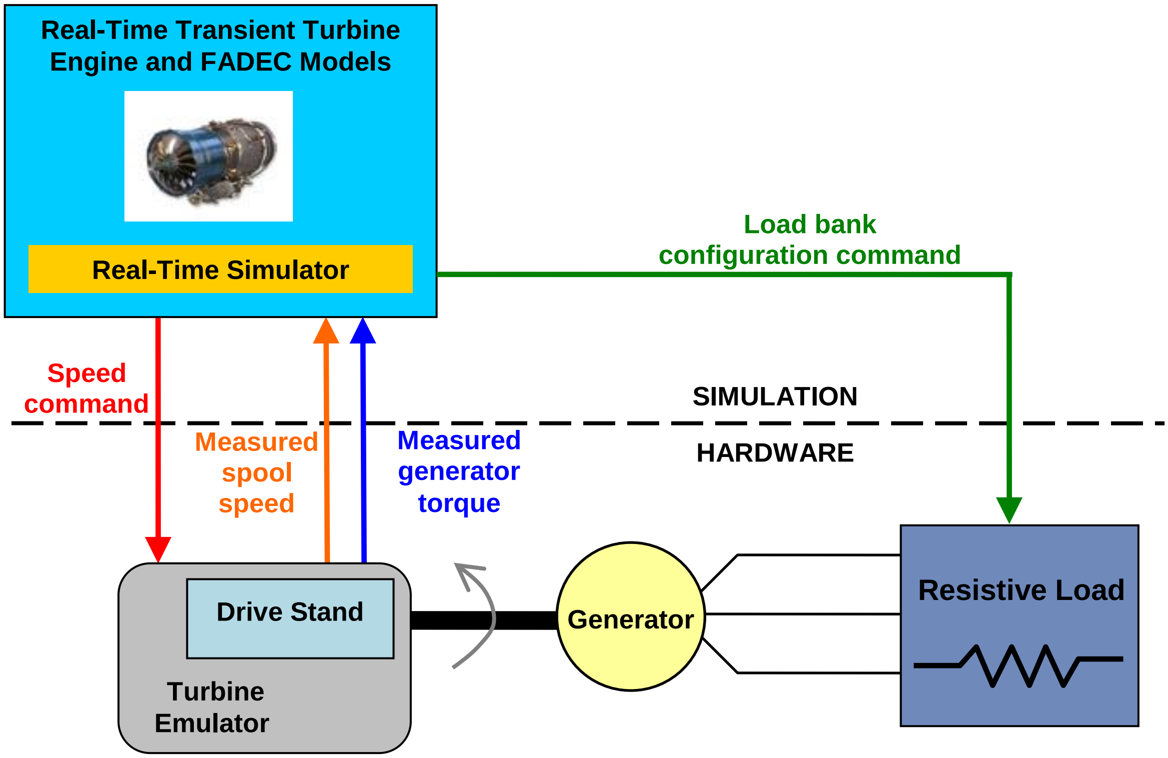

Figure 1. Hardware-in-the-Loop Configuration

The signals themselves are sent into and out of the simulation using analog and digital signals. The spool speed calculated by the model is converted to a command voltage for the drive stand and is sent from the simulation as an analog output. The load bank is controlled by eight digital signals. All possible load bank configurations are put into a lookup table. The desired load is selected from a list in the model and the corresponding digital output pin configuration is sent to the load bank which then applies the load to the generator. There are two feedback signals from the hardware back to the simulation. The first is the torque that the generator puts on the drive stand shaft as measured by a torque transducer. This analog voltage is fed back into the model and a corresponding simulated load is applied to the turbine. The second feedback signal is the drive stand shaft speed as measured by a magnetic speed transducer. This creates a frequency modulated signal which is passed through a frequency to voltage conditioner. The resulting 0-10 VDC signal is fed back into the model and is converted into a speed that can be compared to the commanded signal to capture both accuracy and phase lag.

B. Real-time Simulation

The process of transitioning a model from Simulink to a real-time operating system is a non-trivial task. Three real-time platforms were given strong consideration in this effort. Those different real-time systems have commonalities as well as stark differences. Because the combined engine/FADEC model is in Simulink, it requires MATLAB, Simulink, Real-Time Workshop, and an appropriate compiler for each of the platforms. Real-Time Workshop first generates equivalent C-code for the Simulink blocks. Then it compiles this generated C-code along with the C-wrapper (for the Fortran TERMAP). The resulting object is linked with a library form of the Fortran code and is targeted to the appropriate real-time platform.

The real-time operating system used for the analyses presented in this paper is from National Instruments (NI). With their platform, the Simulink model is compiled and linked into a standard dynamic link library (DLL). Model controlling functions are called from this DLL using the Win32 API (application programming interface) LoadLibrary function. This programming is mostly automated by using NI's Simulation Interface Toolkit (SIT). SIT also assists in passing information between model variables and the I/O board. The real-time operating system itself is Windows-like and supports a major subset of the Win32 API, simplifying much of the process. The required input files can be copied onto the real-time system and are appropriately loaded during model initialization. A graphical interface is developed in NI's LabVIEW to monitor the model, interface with it as it runs, and log data. Some modifications were necessary to configure the NI real-time scheduler to allow the model to converge in hard real-

time. An additional advantage to the NI system is that computing hardware is PC-based, and can be configured from off-the-shelf parts.

V. Testing and Analysis

A preliminary set of results is presented herein which demonstrates that the HIL configuration is capable of running in real-time, coupling a simulated engine with electrical system hardware. Several studies have been done to compare the HIL test results with data generated by running the same engine/control simulation with an idealized generator simulation. Since there is generally good (though not exact) agreement between those data sets, the hypothesis is made that using the hardware generator allows the inter-subsystem dynamics to be more accurately captured. To test this hypothesis, several tests that were run using engine hardware in 2005 are repeated using the HIL configuration.

The first test that compares HIL data to the 2005 test data is a load turn-on transient. For this test, the altitude, Mach number, and TLA are held constant. A large resistive load is applied to the generator by commanding a step change in resistor load bank configuration. The resulting spool speed transient is shown in Figure 2. It can be seen that both data sets show a significant and immediate drop in spool speed when the load is applied. The slope of the speed lines is approximately the same and they settle on approximately the same steady state value. The difference between the data sets is less than 3% (which is acceptable) and is attributed to small differences between the hardware engine and the simulated engine as well as differences in the environmental conditions for the respective tests. The spool speed is unable to recover to its set-point (which is based on altitude, Mach number, and TLA) because the FADEC reduces fuel flow to enforce a maximum turbine inlet temperature.

The corresponding load removal transient is shown in Figure 3. Here, the spool speed surges back to its set-point. As with the load turn-on transient, both the experimental data and the HIL data show the same acceleration rate (slope) and both hit the same maximum during the overshoot. The altitude test data shows less damping in its response as it settles to its final speed.

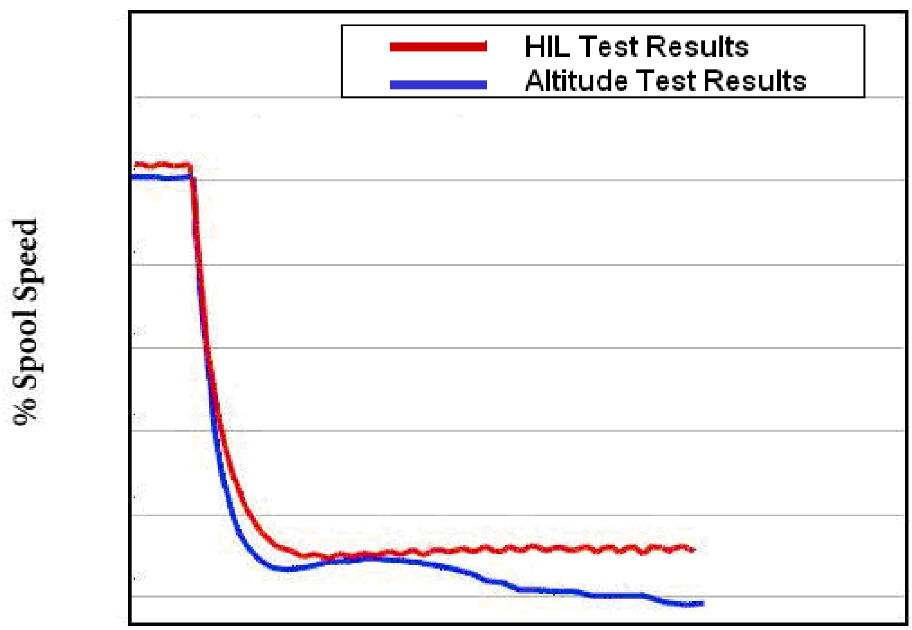

Figure 2. Generator Load Turn-On Transient.

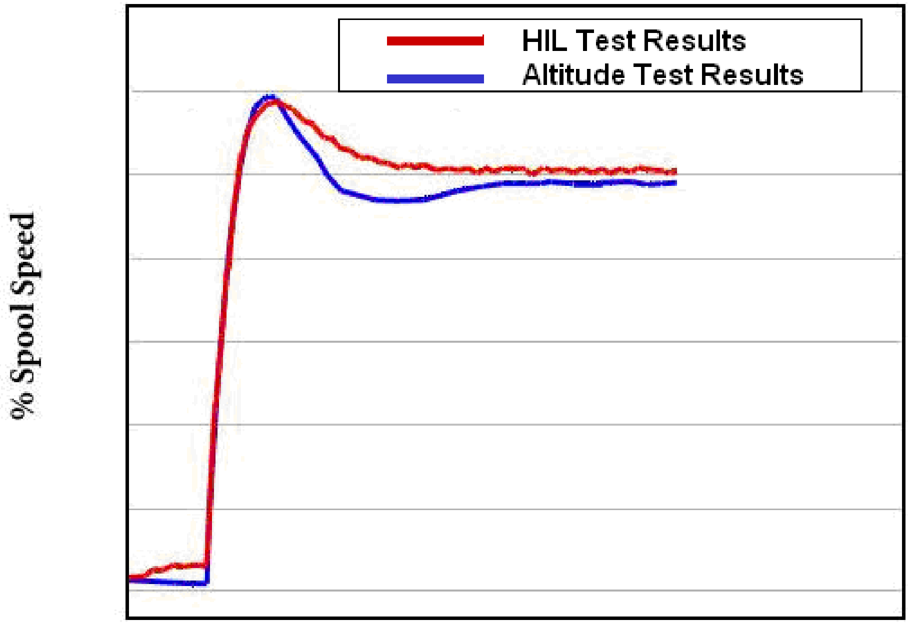

Figure 3. Generator Load Turn-Off Transient.

These figures demonstrate excellent agreement between the experimental data taken in an altitude-simulating wind tunnel in 2005 and the HIL data taken using the same generator connected to a simulated engine. It is key to note that this dynamic, hardware-in-the-loop simulation was able to capture overshoot type characteristics that would not be seen in steady state cycle deck analysis. It is during these transient events that the engine can experience the most stressful conditions in terms of mechanical and thermal stresses and aerodynamic stability.

VI. Conclusion

Heretofore, no study has leveraged the benefits of the HIL concept for investigation of combined thrust and electrical power production of gas turbines using validated models. The analysis done in this effort stresses the importance of accurately capturing system-level dynamics and shows that hardware-in-the-loop is an ideal configuration for performing such tests. An HIL setup ideally combines the accurate and timely response of hardware with the safety and low cost of simulation. Requirements for a successful HIL test include accurate models, appropriate hardware-software interfaces, and a real-time platform capable of executing the model in hard real-time.

This effort was able to successfully demonstrate the integration of a Rolls-Royce developed and validated engine simulation with generator hardware. The HIL results were able to match the results of an idealized generator load with the expected level of accuracy. This verified that there were dynamic interactions between the engine and power subsystems that were worth investigating. More importantly, the HIL data was able to match data that was taken from an engine test cell where the engine was run in an altitude-simulating wind tunnel and the same generator was loaded and unloaded in the same way. This demonstrates that HIL is a viable test platform that is an accurate and cost-effective way to investigate integrated system dynamics.

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